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SUMMARY

In extrapolating presently used gaseous-hydrogen heat-transfer correlations to conditions far removed from the experimental points, unexplained behavior in the predicted results of such equations has been noted. Experimentally, under the proper circumstances, a small reduction in the bulk hydrogen temperature can cause an increase rather than a decrease in the surface temperature of a constant-heat-flux test specimen. Mathematically, the correlations used at the present time exhibit the same effect, but usually to a much greater degree, and result in some questionable values at higher surface temperatures.

To determine whether a more accurate method of predicting heat transfer at high surface- to bulk-temperature ratios is available, various correlations were examined. The result of this examination indicates that a correlation is available which achieves an appreciable decrease in the data scatter and at the same time reduces (but does not eliminate) the anomaly noted with equations now commonly used. The range of variables considered in this investigation were: (1) the ratio of distance from entrance L to hydraulic diameter D between 10 and 240, (2) the bulk fluid temperature from 200° to 2800° R, and (3) the ratio of wall temperature to bulk fluid temperature between 1.1 and 8.0.

The application of this improved correlation to a particular problem encountered in nuclear rocket reactor design is also discussed.

INTRODUCTION

In the design of nuclear reactors for rocket propulsion, it is extremely important to achieve the highest propulsion-gas temperature possible in order to obtain the most efficient performance of the rocket. To accomplish this with a minimum-sized reactor, the heat-producing fuel elements must be operated as near their maximum allowable temperature as possible. This can be done by optimizing the nuclear heat generation profile and distributing the gas flow in such a manner as to maintain a nearly uniform fuel-element temperature over the entire reactor core.

While there are certain physical limitations that prevent the actual attainment of such an idealized condition, it is essential to know both the nuclear and the heat-transfer characteristics of the system quite well in order to approach this goal to any extent at all.

Heat transfer of gaseous hydrogen and other gases has been widely studied in the past several years (refs. 1 to 8). The results of this work have been correlated by a variety of methods, which, in general, can be represented by an empirical equation of the form

$$Nu = KRe^{A}Pr^{B}\left(\frac{T_w}{T_b}\right)^{C} \tag{1}$$

where the physical properties involved are evaluated at some reference temperature such as bulk, film, or wall temperature. (All symbols are defined in the appendix.)

Equation (1) is sometimes modified by the inclusion of an empirical correction factor to account for entrance effects. For example, $1 + 0.3(L/D)^{-0.7}$ is such a factor in the following equation (ref. 9):

$$Nu_b = 0.025\ Re_b^{0.8}Pr_b^{0.4}\left(\frac{T_w}{T_b}\right)^{0.55}\left[1 + 0.3\left(\frac{L}{D}\right)^{-0.7}\right] \tag{2}$$

Since this factor is relatively small for values of L/D in excess of 10 (i.e., less than 6 percent), it is of negligible concern in the problem under consideration in this report and will be omitted for simplification throughout the remainder of the discussion.

Much of the work done at the Lewis Research Center (refs. 1 to 4) has indicated that the use of a modified Reynolds number correlates the data reasonably well if the physical properties are evaluated at either the film or the surface temperature and an appropriate constant K is used. The design equation commonly used to predict the local heat-transfer characteristics of gaseous hydrogen has been based on this work and utilizes the following type of equation:

$$\frac{hD}{k_f} = 0.021\left(\frac{GD}{\mu_f}\right)^{0.8}\left(\frac{T_b}{T_f}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)_f^{0.4} \tag{3}$$

The mechanism of convective heat transfer is such that the amount of energy transferred to a flowing fluid (the coolant) is equal to the product of the coefficient h (defined by an equation such as eq. (3)) and the difference between the surface temperature and the bulk temperature of the coolant:

$$\frac{Q}{S} = h(T_w - T_b) \tag{4}$$

Equation (4) indicates that lowering the temperature of the cooling stream some amount could lower the temperature of a body in which the heat generation rate Q/S is constant because, in order to balance the equation, the temperature difference must also remain constant. Although intuitively this same reasoning seems logical (i.e., a colder fluid should result in a lower body temperature), it implies that the coefficient h must also remain constant during this process. A close examination of equation (3), however, shows that lowering the bulk temperature does not necessarily preclude the possibility of a reduction in the convective coefficient. Here it would be necessary for the surface temperature to rise in order to balance equation (4) for constant flux.

Experimentally, under the proper set of conditions, the phenomenon of increasing the surface temperature by decreasing the hydrogen gas temperature has been observed. For example, in several of the runs from reference 4 a reduction in the incoming gas temperature caused a rise in the surface temperature, or in other instances caused less of a decrease than would be expected. Table I illustrates this strange effect; it can be seen that, for runs 49 and 96, a 274° to 283° R decrease in the hydrogen temperature resulted in a decrease of only 101° to 138° R in the local surface temperature. For runs 68 and 115 the values indicate an actual rise of 51° to 150° R in the local surface temperature for a 340° to 351° R decrease in the bulk gas temperature.

Most of the data used to arrive at this heat-transfer correlation (eq. (3)) have been for a range of T_w/T_b below 4.0. It is, therefore, not surprising that extrapolation of this equation to higher temperature ratios could result in some deviation from experimentally determined points. Several investigations (refs. 3 and 4) have recently been conducted in an

TABLE I. - COMPARISON OF SEVERAL EXPERIMENTAL RUNS FROM REFERENCE 4

Run	Ratio of distance from entrance to diameter, L/D (a)	Flow, lb/sec (a)	Heat input, Btu/sec (a)	Temperature, °R	
				Bulk, T_b (a)	Wall, T_w (a)
49	13.3	0.0053	0.340	558	889
96	13.3	.0053	.340	275	751
	Temperature change			-283	-138
68	13.3	0.0179	1.521	611	1175
115	13.3	.0175	1.513	260	1226
	Temperature change			-351	+51
49	45	0.0053	0.341	669	1027
96	45	.0053	.340	395	926
	Temperature change			-274	-101
68	45	0.0179	1.517	758	1396
115	45	.0175	1.493	418	1546
	Temperature change			-340	+150

[a]Local values.

effort to substantiate the correlation over a larger range. While the results did agree fairly well with the present method (eq. (3)), several areas were noted in which the equation lacked the ability to predict local heat-transfer characteristics accurately. Many of these discrepancies have been associated with higher surface- to bulk-temperature ratios that are of particular interest in nuclear-rocket design.

When this empirical correlation (eq. (3)) is used to determine the heat transfer within a high temperature nuclear-rocket reactor, a problem is frequently encountered. A large increase in predicted surface temperature results from a relatively small decrease in the bulk temperature of the gas. Because such effects have been noted experimentally, it is not strange that a true correlation of such data would predict similar increases in the surface temperature for cases where the incoming gas temperature was reduced. Logically, however, a decrease in the surface temperature of the material being cooled might be expected. In many cases, the predicted increase was greatly magnified and resulted in extremely high surface temperatures for small changes in the bulk temperature.

To explain more specifically this strange behavior encountered in using the film correlation (eq. (3)) for nuclear reactor design, it is probably best to show the calculations involved for a typical case. If a set of conditions is assumed at a point near the entrance to a hypothetical reactor such that a given set of conditions exists at a design point (point 0) and then the incoming bulk temperature $T_{b,1}$ is reduced by a certain amount, the predicted surface temperature $T_{w,1}$ of the fuel element increases at a greatly magnified rate, which is a function of the initial surface- to bulk-temperature ratio $(T_w/T_b)_0$. This can be seen mathematically by rewriting equation (3) for a case where the geometry and flow rate are fixed; that is,

$$h = \text{const}\left(\frac{c_p^{0.4}k^{0.6}}{\mu^{0.4}}\right)_f\left(\frac{T_b}{T_f}\right)^{0.8} \tag{5}$$

The ratio of the heat-transfer coefficients at the design point (point 0) and the off-design point (point 1) can then be expressed as follows:

$$\frac{h_0}{h_1} = \frac{\left(\frac{c_p^{0.4}k^{0.6}}{\mu^{0.4}}\right)_{f,0}\left(\frac{T_b}{T_f}\right)_0^{0.8}}{\left(\frac{c_p^{0.4}k^{0.6}}{\mu^{0.4}}\right)_{f,1}\left(\frac{T_b}{T_f}\right)_1^{0.8}} \tag{6}$$

By inclusion of the relation between the heat flux, the convection coefficient, the temperature difference as defined by equation (4), and the definition of the film temperature

$$T_f = \frac{T_b + T_w}{2} \tag{7}$$

equation (6) may be expressed as follows for constant power:

$$\frac{(T_w - T_b)_1}{(T_w - T_b)_0} = \frac{\varphi_0}{\varphi_1}\left[\frac{1 + \left(\frac{T_w}{T_b}\right)_1}{1 + \left(\frac{T_w}{T_b}\right)_0}\right]^{0.8} \tag{8}$$

where

$$\varphi_i = \left(\frac{c_p^{0.4} k^{0.6}}{\mu^{0.4}}\right)_{f,i}$$

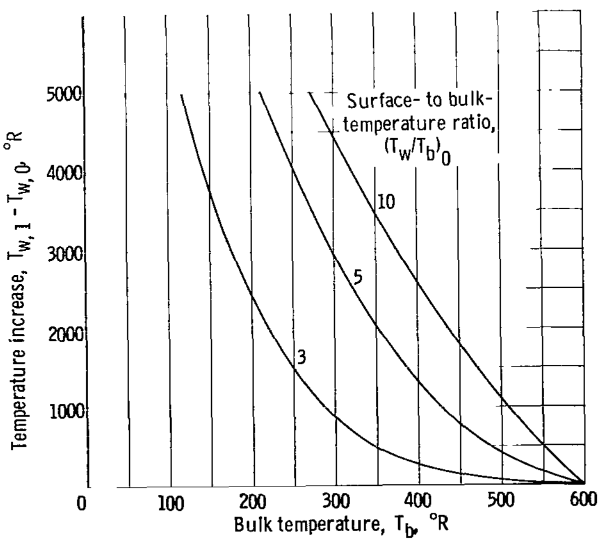


Figure 1. - Predicted increase in surface temperature due to decrease in bulk temperature.

Figure 1 shows the result of applying equation (8) to a series of problems in which the initial bulk temperature $T_{b,0}$ was fixed at 600° R while the initial wall temperature $T_{w,0}$ and the final bulk temperature $T_{b,1}$ were varied over a range of conditions. The final wall temperature was determined from equation (8) by using the physical properties of normal hydrogen from King (ref. 10). (Note that the use of a different set of properties and/or the use of para-hydrogen rather than normal hydrogen might make a small difference in the results, but the conclusions would be the same.) It can readily be seen, for example, that at an initial temperature ratio of 10, a reduction in

TABLE II. - TYPICAL VALUES USED IN APPLYING EQUATION (8)

Variable	Initial value	Final value	Actual change	Relative change, percent
Bulk temperature, T_b, °R	600	400	-200	-33
Surface temperature, T_w, °R	3000	4360	1360	45
Film temperature, T_f, °R	1800	2380	580	32
Surface- to bulk-temperature ratio, T_w/T_b	5	10.9	5.9	118
Temperature difference, $T_w - T_b$, °R	2400	3960	1560	65
Ratio of physical properties, φ	0.481	0.505	0.024	5

bulk temperature of as little as 100° R causes an increase of about 1000° R in the predicted surface temperature; for a reduction of 200° R, the increase is over 2500° R.

Not all of this predicted increase can be attributed to a change in the physical properties of the gas. In fact, a relatively small change in the property ratio φ_0/φ_1 occurs for a seemingly large variation in the associated temperatures. This can be seen by comparing the values for a typical set of calculations (table II). Table II shows that while the physical properties only vary by 5 percent, the predicted increase in the temperature difference, which is an inverse measure of the convection coefficient, is 65 percent. Most of this seemingly high rate of increase can therefore be attributed to the mathematical formulation of equation (3), which tends to magnify small changes at high surface- to bulk-temperature ratios.

Extrapolation of the preceding results to still lower bulk temperatures or to higher wall- to bulk-temperature ratios would indicate that the fuel-element temperature gets hotter as the coolant becomes colder and eventually even approaches an infinite value.

While such unlimited extrapolation is not possible because of certain physical properties (i.e., the fuel elements may melt, two-phase flow occurs, etc.), the implications of this numerical analysis do point out the reason for the chief concern of the reactor designer. Although it seems unlikely, if this correlation (eq. (3)) were indeed true over the entire range of conditions encountered in a nuclear rocket reactor, it would be impossible to design the system to full capacity since the possibility of a decrease in bulk temperature at any time during operation near full power would exist. For if the reactor were initially designed to obtain maximum performance (i.e., operation at maximum fuel-element temperature), a decrease in the incoming gas temperature could result in severe damage to the fuel elements.

Because of the results shown in figure 1, it seems only reasonable to investigate other methods of calculating the heat-transfer coefficient of gaseous hydrogen at high surface- to bulk-temperature ratios to determine whether any of the existing correlations fit the data better than the film method and, if so, to see whether such an equation reduces the magnitude of the problem previously described.

McCarthy and Wolf Correlation

Experiments conducted by Wolf (ref. 5) for $1.44 < T_w/T_b < 9.2$ have been correlated with an equation of the type presently used for some of the NERVA (ref. 9) heat-transfer calculations

$$Nu_b = 0.025\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right)^{-0.55} \tag{9}$$

While the "average" deviation is within ±10 percent of the test results, some deviations of the order of 100 percent do result between the experimental and the predicted points when this correlation is used.

To compare the magnitudes of the heat-transfer coefficients predicted by equations (3) and (9), a method suggested by Dalle Donne (ref. 8) is used in which the following approximations are made:

$$\left(\frac{\mu_1}{\mu_0}\right) \approx \left(\frac{T_1}{T_0}\right)^{\alpha} \tag{10a}$$

$$\left(\frac{k_1}{k_0}\right) \approx \left(\frac{T_1}{T_0}\right)^{\beta} \tag{10b}$$

$$\left(\frac{c_{p,1}}{c_{p,0}}\right) \approx \left(\frac{T_1}{T_0}\right)^{\gamma} \tag{10c}$$

While these assumptions are not exactly correct, there is an approximate logarithmic relation for the properties of hydrogen over a range of temperatures from about 300° to 3000° R. Over this range the values of the constants are

$$\alpha \approxeq 0.67$$

$$\beta \approxeq 0.8$$

$$\gamma \approxeq 0.15$$

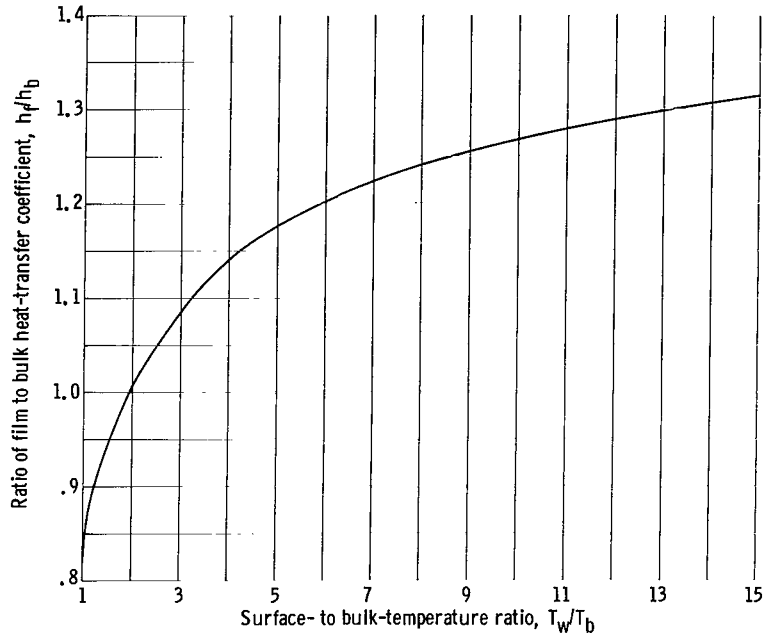


Figure 2. - Approximate difference in film coefficient between film and Wolf correlation.

Using these physical property relations and dividing equation (3) by equation (9) results in a ratio of the heat-transfer coefficient predicted by the two methods, which is

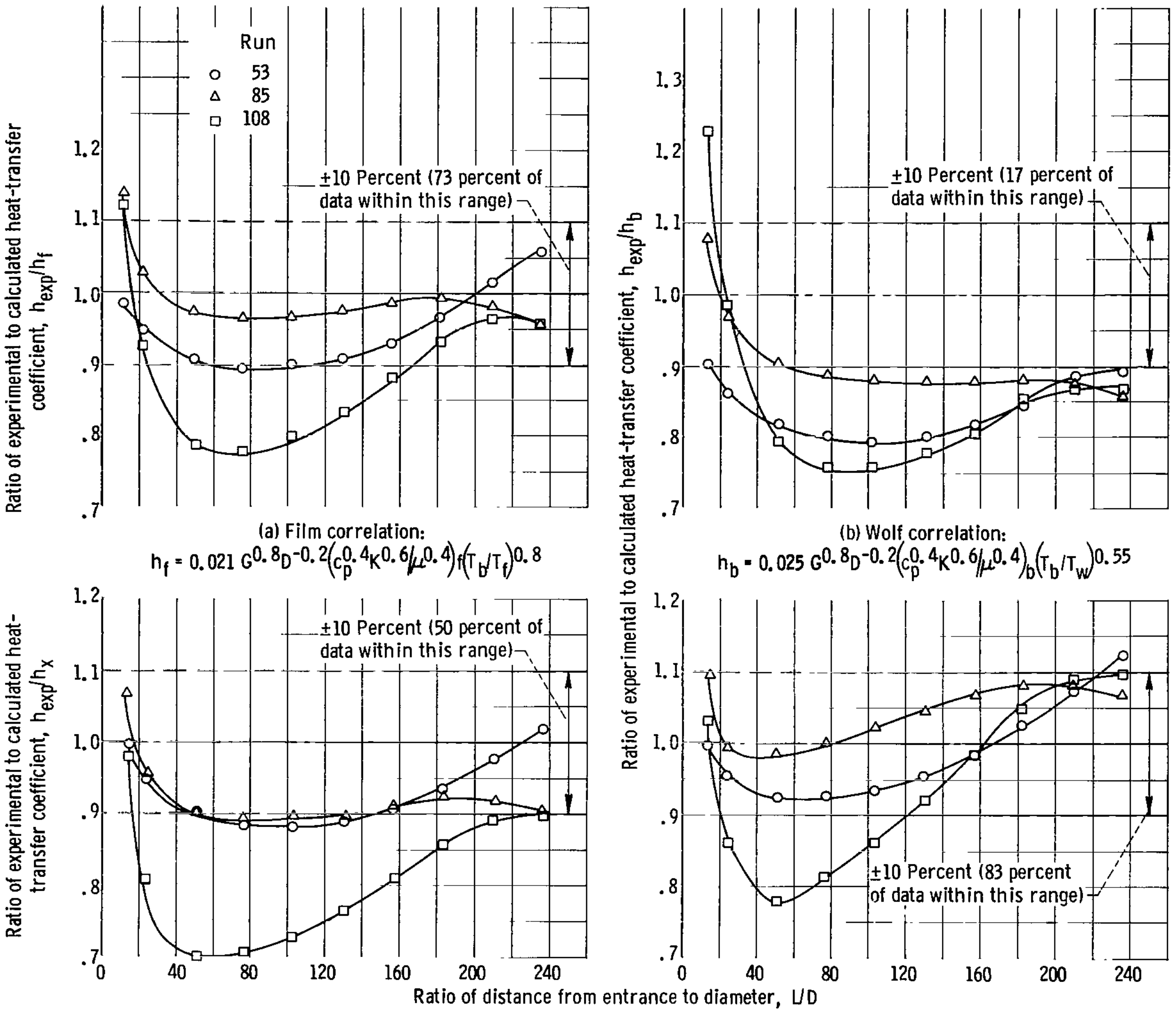
$$\frac{h_f}{h_b} = 0.84\left(\frac{T_b}{T_f}\right)^n \left(\frac{T_w}{T_b}\right)^{0.55} \tag{11a}$$

where $n = 0.8 + 0.4\alpha - 0.6\beta - 0.4\gamma \cong 0.5$ and h_f and h_b refer to the coefficients determined by equations (3) and (9), respectively.

Rewriting equation (11a) by employing the definition of the average film temperature yields

$$\frac{h_f}{h_b} = 0.84\left(\frac{2}{1 + \frac{T_w}{T_b}}\right)^n \left(\frac{T_w}{T_b}\right)^{0.55} \tag{11b}$$

A plot of equation (11b) is shown in figure 2 and indicates an approximate discrepancy between the two equations of over 25 percent for wall- to bulk-temperature ratios greater than 10. The magnitude of this discrepancy does not explain the much larger (100 percent) local deviations in the experimental data (ref. 5). Since the ratio h_f/h_b is greater



(a) Film correlation: $h_f = 0.021\, G^{0.8} D^{-0.2} \left(c_p^{0.4} K^{0.6} / \mu^{0.4}\right)_f (T_b/T_f)^{0.8}$

(b) Wolf correlation: $h_b = 0.025\, G^{0.8} D^{-0.2} \left(c_p^{0.4} K^{0.6} / \mu^{0.4}\right)_b (T_b/T_w)^{0.55}$

(c) Deissler correlation: $Nu_x = Re_x^{0.75}/31$ where $x = 0.4$.

(d) Modified Dalle Donne correlation: $Nu_b = 0.021\, Re_b^{0.8} Pr_b^{0.4} (T_w/T_b)^{-[0.29+0.0019(L/D)]}$

Figure 3. - Comparison of experimental and calculated heat-transfer coefficients using various correlations. (Data taken from ref. 4.)

than 1 for the higher values of T_w/T_b, the predicted surface temperature associated with equation (9) will be higher and the strange effect shown in figure 1 (p. 6) will only be more exaggerated. To make a true comparison of this correlation with equation (3), however, typical experimental runs from reference 4 were chosen. These experiments were characterized by two types of data, one that was obtained with the inlet gas uncooled and easily correlated with the film temperature (eq. (3)) and one that was obtained with the inlet gas cooled by a liquid-nitrogen precooler and not easily correlated in this manner. Figure 3(a) shows the ratio of experimental to calculated heat-transfer coefficient as a function of L/D in the test section for these typical runs. It can easily be seen that, while the calculated value for the "hot" run (85) agrees reasonably well with the experimental value, the results for the "cold" run (108) vary markedly from the true value and drop 20 to 25 percent below the desired value. The third run (53) is an intermediate type, the data falling part way between the other two extremes.

This seemingly inconsistent behavior cannot be satisfactorily explained by the film correlation, nor can it be corrected by altering the constant in the equation because this method only tends to improve the results of one run at the expense of another. Since the spread of these runs represents a severe test of any correlation, they were subsequently used as a test of those correlations that are considered in this report.

Figure 3(b) shows the result of applying equation (9) to the three runs previously described. A comparison of figures 3(a) and (b) shows that the error has been increased by the use of equation (9) and, therefore, this type of correlation appears to be even less satisfactory than that presently used (eq. (3)) for predicting the heat transfer of gaseous hydrogen at high surface- to bulk-temperature ratios. It should be noted that a reduction in the correlation constant from 0.025 to about 0.021 might tend to make this equation (eq. (9)) acceptable. Such action, however, would substantially increase the deviation of the original data used in arriving at this correlation (ref. 5).

Deissler Method

An analytical method, developed by Deissler (ref. 11) for air and supercritical water and later expanded (ref. 12) to include hydrogen and other variable-property gases, uses a reference temperature to evaluate the physical properties in the heat-transfer equation. This reference temperature, defined as

$$T_x \equiv T_b + x(T_w - T_b) \tag{12}$$

coincides with the defined film temperature T_f currently used when $x = 0.5$. For $x = 0$ or 1.0, the properties are evaluated at the bulk or the wall temperature, respectively.

Deissler's analysis for hydrogen (fig. 4) indicates that x varies from about 0.2 to 0.42 depending on the Reynolds number and the surface temperature involved, but that, in general, the available data could be correlated at a value of $x = 0.4$; that is,

$$Nu_x = \frac{Re_x^{0.75}}{31} \tag{13}$$

where $x = 0.4$. Jackson and Barnes (ref. 12, discussion) point out that several empirical values of x for hydrogen have been obtained from experimental results (0.4 (ref. 6)

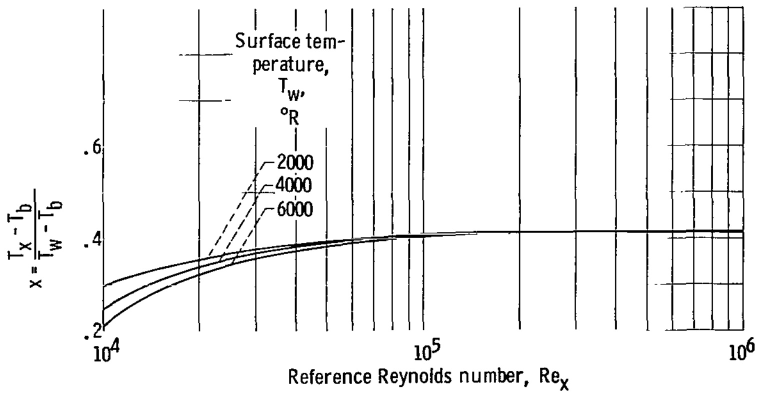


Figure 4. - Value of x used to determine reference temperature. (Data taken from ref. 12.)

and 0.44 (ref. 7)) and have been shown to be in good agreement with the aforementioned value.

One obvious disadvantage of using this reference temperature to solve a particular problem is that it is necessary to iterate the solution because the proper value of x depends on several quantities (Re_x and T_w) that are dependent on the final value of the calculated wall temperature. Even though this extra iteration limits the flexibility of this type of correlation, using it is still advantageous if the equation reduces the spread in the experimental data and improves the problem encountered at high temperature ratios.

To visualize qualitatively the amount of correction a reference temperature correlation does produce, equation (13) was applied to the three experimental runs of reference 4. The results are shown in figure 3(c), and it can readily be seen that this correlation (eq. (13)) does not predict the heat-transfer coefficient as well as equation (3) although the spread is about the same for the three cases shown.

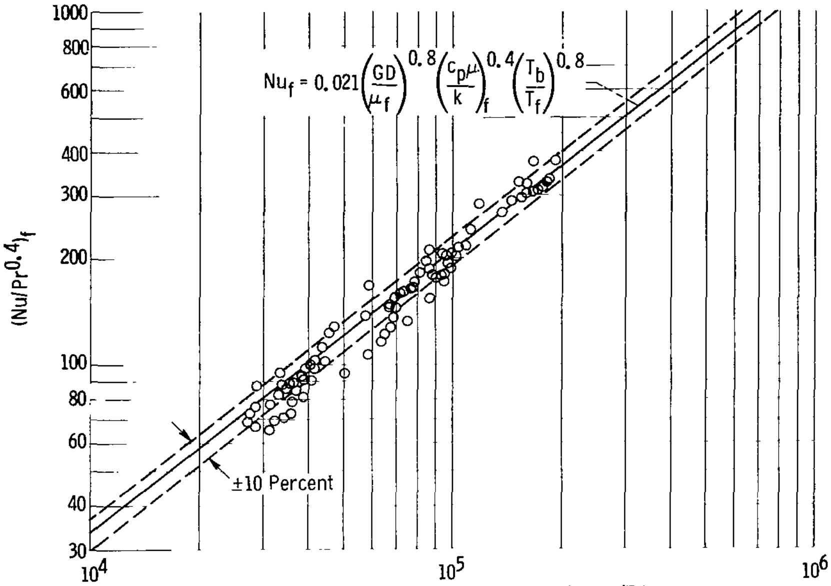
Dalle Donne and Bowditch Correlation

As a result of a literature survey and an experimental program conducted on the Euratom Dragon reactor project, Dalle Donne and Bowditch (ref. 8) were able to correlate the heat transfer of helium and air using an equation of the form

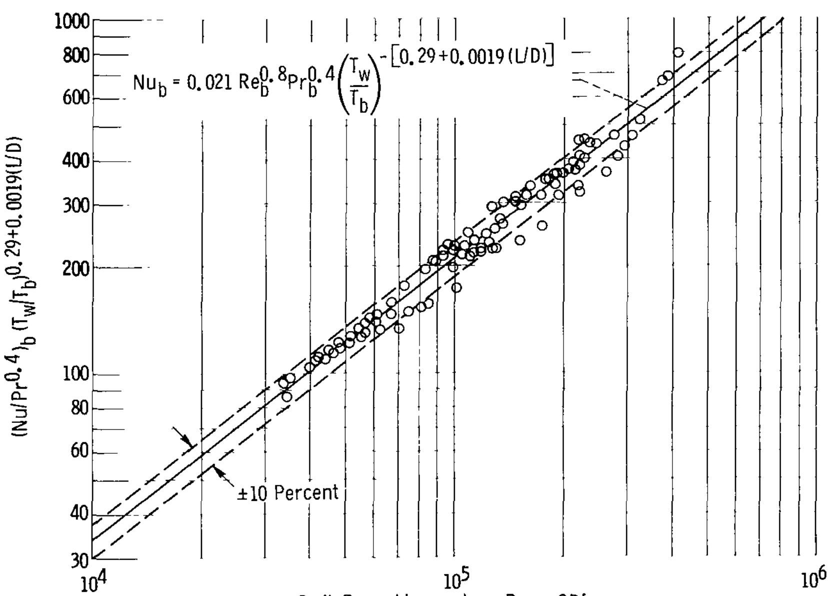
$$Nu_b = 0.024\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right)^{-C} \tag{14}$$

which is nearly identical to the Wolf relation (eq. (9)) where C = 0.55.

Because of certain inconsistencies noted in the experimental data, however, it was



(a) Film correlation.



(b) Modified Dalle Donne correlation.

Figure 5. - Nusselt-Prandtl-Reynolds relation plotted using various correlations. (Data taken from ref. 4.)

necessary to modify the value of C to include an L/D correction term by which the data were correlated to ±8 percent, namely, $C = 0.29 + 0.0056$ L/D. While the authors of reference 8 offer qualitative reasons for the L/D term, no completely satisfactory explanation is currently available although such a dependency on L/D has been noted by some experimenters (ref. 4).

At low values of L/D, the value of C is nearly equal to 0.29 and increases as L/D becomes larger. Note that, for L/D = 46, C = 0.55, the same value used in the Wolf correlation (eq. (9)), which was evolved for $21 < L/D < 67$ or a mean value of L/D = 44. To investigate the applicability of this type of correlation to the present problem, equation (14) was applied to the three reference cases previously used. It was found that the L/D correction factor was too large for this application and that a more useful form of the equation was

$$Nu_b = 0.021\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right)^{-C} \tag{15}$$

where $C = 0.29 + 0.0019$ L/D.

Results of this modified equation are shown in figure 3(d), which indicates that, while this correlation does not completely resolve the odd behavior of this experimental series, it does statistically reduce the number of points that fall outside the ±10 percent margin. To determine more specifically whether this correlation does indeed improve the scatter, however, many more points were arbitrarily chosen from similar data (ref. 4). Figures 5(a) and (b) show the more familiar Nusselt-Prandtl-Reynolds relation for these points, which were plotted using the film correlation (eq. (3)) and the modified Dalle Donne method (eq. (15)). Close examination of these two figures indicates that the spread of the data is reduced when the latter equation is used and that only about half as many points fall outside the ±10 percent margin in this case.

One region where equation (15) should be used cautiously is at very large L/D ratios. Since the temperature ratio is raised to a power that approaches a large value at very large length-to-diameter ratios, the predicted film coefficient will approach zero unless the surface- to bulk-temperature ratio is restricted to about 1.0. Fortunately, in most nuclear reactors, the design is such that the gas and surface temperature near the reactor exit approach each other so that the aforementioned restriction ($T_w/T_b \cong 1.0$) may apply at the larger L/D ratios.

Simoneau and Hendricks Correlation

A recent correlation has been presented (ref. 13) that attempts to simplify the com-

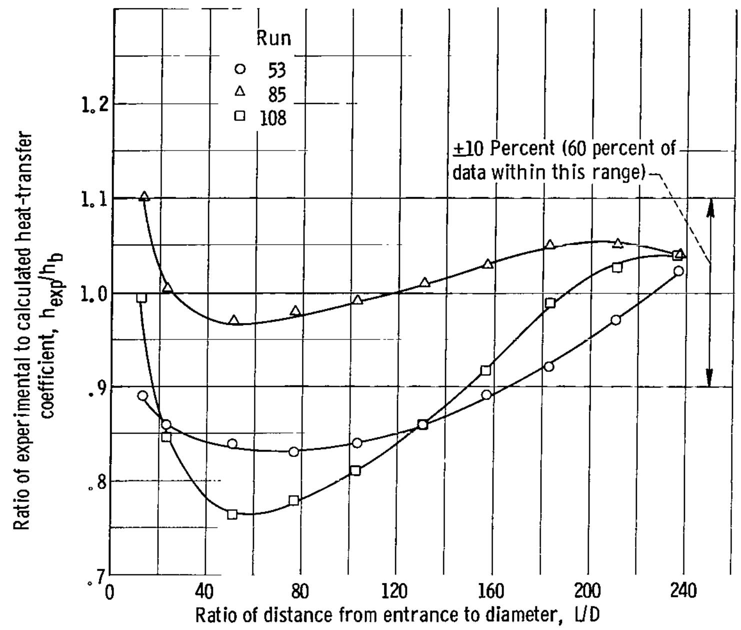


Figure 6. - Comparison of experimental and calculated heat-transfer coefficients using Simoneau-Hendricks correlation, $h_b = 0.048\,G^{0.8}D^{-0.2}(T_w/T_b)^{-0.5}$. (Data taken from ref. 4.)

putation of the heat-transfer coefficient by eliminating the physical properties of the gas. For hydrogen, this correlation is

$$h = 0.048\,G^{0.8}D^{-0.2}\left(\frac{T_w}{T_b}\right)^{-0.5} \tag{16}$$

To determine whether this simplified correlation has any merit for the application presented in this report, the three typical cases previously described were analyzed by using equation (16). Figure 6 presents the results of these calculations and shows statistically less agreement than either the film correlation (fig. 3(a)) or the modified Dalle Donne correlation (fig. 3(d)).

While this type of equation would undoubtedly simplify the calculational procedures involved in determining the heat-transfer coefficient, it is doubtful whether elimination of the gas properties, particularly in the lower temperature region ($T_b < 200^\circ$ F), could improve the discrepancy between calculated and experimental values.

Correlation of Other Data

Since the modified Dalle Donne equation (eq. (15)) shows the most promise from the standpoint of a tighter correlation, a greater number of the experimental points com-

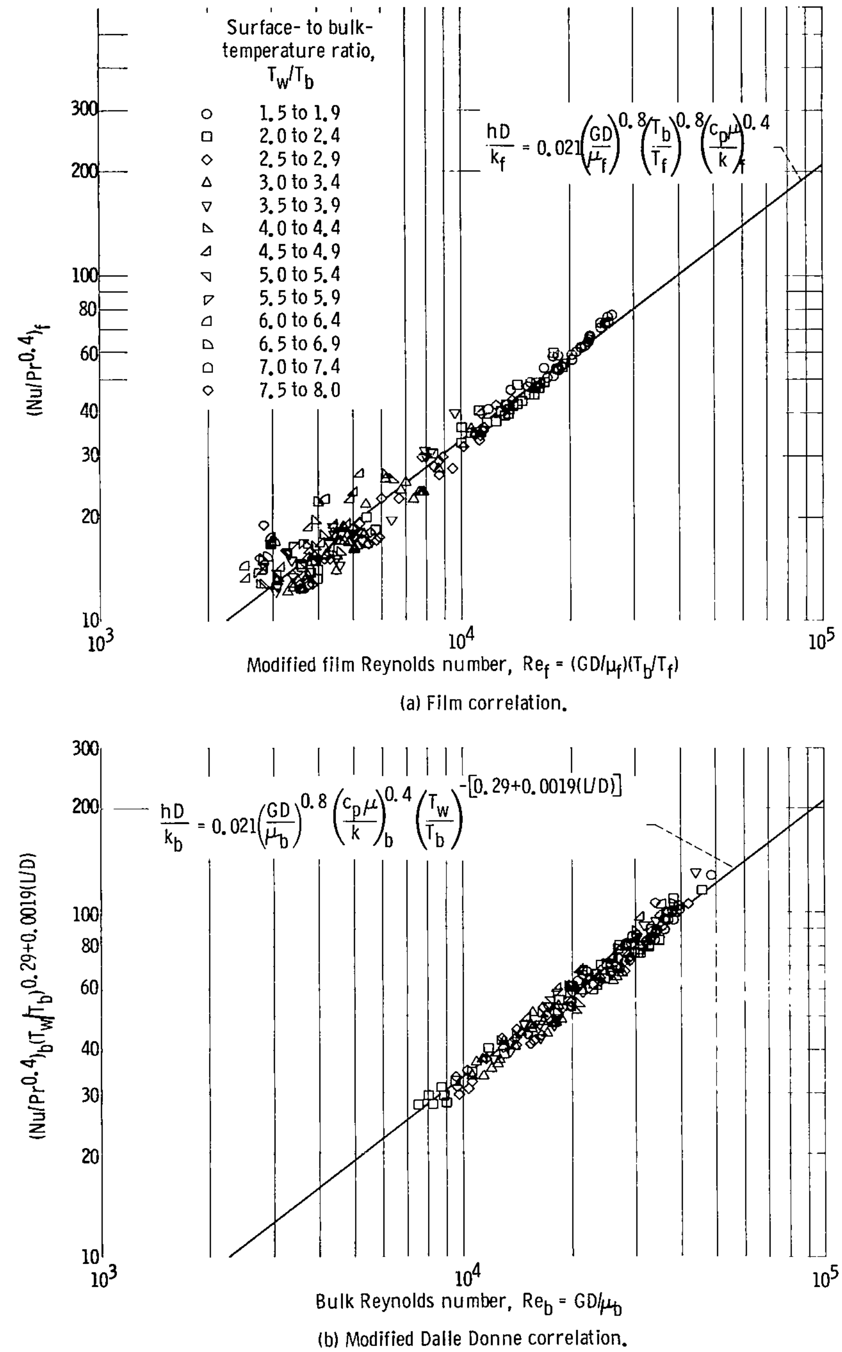


Figure 7. - Variation of Nusselt-Prandtl relation with Reynolds number. (Data taken from refs. 3 and 14.)

prising data from references 3 and 14 were examined by this method.

The experimental data are shown in figure 7(a) correlated by the conventional method of evaluating the physical properties and density at film temperature. A large deviation in the data correlated in this manner occurs, but it is no larger than that in the data of references 5 and 13. This deviation can be reduced by a large amount by using equation (15), as can be seen in figure 7(b). Most of the data agree to within ±10 percent.

This reduction in spread is important in reactor design not only because it increases the confidence level of the correlation directly, but because it decreases the magnitude of the "hot-channel" factor that is normally applied to the determination of maximum surface temperature. Such a factor is used for design calculations when a maximum surface-temperature criterion exists and reflects the possibility that conditions similar to those of the experimental points falling below the best-fit curve of the correlation could occur in the reactor, resulting in a reduced film coefficient and, consequently, a higher surface temperature.

Application to Nuclear Rocket Reactor Problem

To ascertain the extent to which this modified correlation (eq. (15)) helps or hinders the nuclear rocket reactor design, a representative problem was chosen that would illustrate the phenomena discussed in the INTRODUCTION of this report. For this example, a point near the entrance of the reactor (L/D = 15) was chosen for simplicity because at this point the bulk temperature is nearly coincidental with the inlet temperature and, therefore, it is not necessary to calculate temperature rises to the point under consideration.

If the heat flux and mass flow rate remain the same, a temperature ratio, similar to equation (8), which relates the values at the design point (point 0) and the off-design point (point 1), can be expressed as

$$\frac{\left(T_w - T_b\right)_1}{\left(T_w - T_b\right)_0} = \frac{\varphi_0}{\varphi_1}\left[\frac{\left(\frac{T_w}{T_b}\right)_1}{\left(\frac{T_w}{T_b}\right)_0}\right]^C \tag{17}$$

where

$$\varphi = \left(\frac{c_p^{0.4}k^{0.6}}{\mu^{0.4}}\right)_b$$

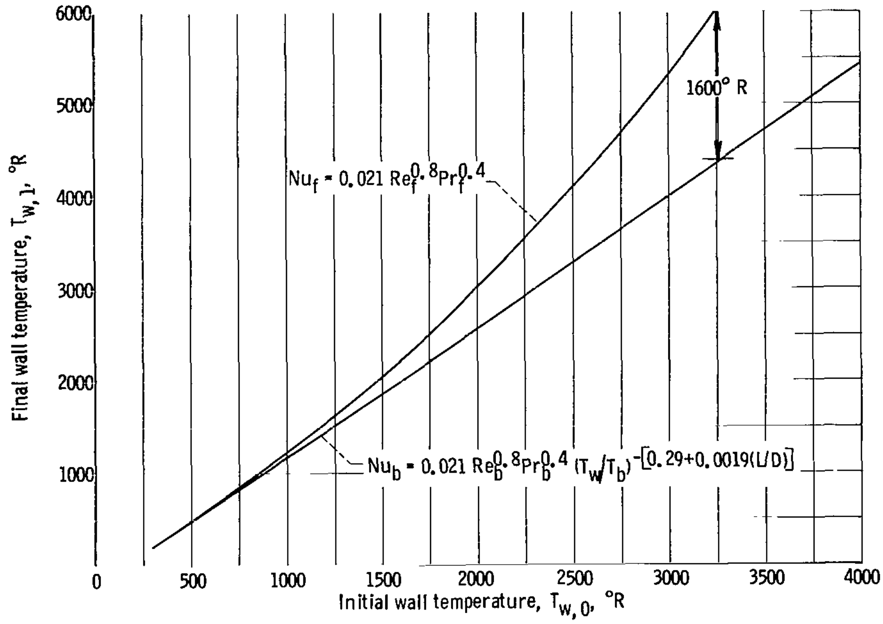


Figure 8. - Predicted wall temperature increase due to decrease in bulk temperature. Ratio of distance from entrance to diameter, L/D, 15; initial bulk temperature, 300° R; final bulk temperature, 200° R.

An initial bulk temperature of 300° R and a final bulk temperature of 200° R were chosen to determine an initial and final wall temperature by both the film correlation ratio (eq. (8)) and the revised Dalle Donne method (eq. (17)). The result of this numerical exercise, shown in figure 8, indicates a considerable difference in the predicted final wall temperature between the two methods. For example, at an initial wall temperature of 3300° R, the film correlation predicts a final temperature of approximately 6000° R; whereas the other method predicts a final temperature of 4400° R, a difference of 1600° R.

To the reactor designer, this huge difference can be interpreted in several ways. First, if it were possible to encounter a local 100° R decrease in the bulk temperature during the operation of the reactor, and providing the axial flux distribution remained constant, the use of the film correlation would require that the reactor be derated to about 70 percent of the power allowed by the alternate method of calculating surface temperature. Secondly, if it were assumed that such a difference could exist over the entire length of the reactor, the size of the core utilizing the film method would have to be nearly 35 percent larger in surface area to transfer the same amount of power as the other method. Lastly, if the melting temperature of the fuel elements was between 4400° and 6000° R, the one method would allow operation of a given reactor at full power; whereas the other method would predict catastrophic melting of the nuclear core under the same conditions.

The modified Dalle Donne correlation may be conservative or unconservative at surface- to bulk-temperature ratios greater than 10; however, since it is impossible to ascertain exactly which without experimental verification, the present method must be extrapolated to include conditions similar to those used in the sample problem and those that will be encountered in a nuclear reactor. Whether this method is more exact than the film method (or other methods) can only be inferred from the correlation of existing data, which appears to be much better using this method.

This correlation appears to satisfy both objectives of this report, namely, (1) to find a correlation that improves the scatter in existing experimental data and (2) to see whether such an improved correlation decreases the magnitude of the predicted surface temperature associated with a decrease in the bulk temperature so that the results agree more closely with experimental observations.

CONCLUDING REMARKS

As a result of the calculations performed for this report, it appears that the spread in existing experimental data can be substantially reduced by using the modified Dalle Donne correlation.

The experimental data correlated in this manner covered the following range of variables:

1. Ratio of distance from entrance L to hydraulic diameter D between 10 and 240
2. Bulk fluid temperature from 200° to 2800° R
3. Ratio of wall temperature to bulk fluid temperature between 1.1 and 8.0

Within these limits imposed by the presently available experiments, the modified Dalle Donne correlation appears to be superior to the other correlations considered. While extrapolation to regions far removed from these values still contains an element of risk, this correlation can be used with at least the same, and possibly a greater, degree of confidence that exists in other correlations.

Since no theoretical reason exists that satisfactorily explains the need for the L/D correction term, further experimentation should be conducted at the higher surface- to bulk-temperature ratios to substantiate this correlation.

For design application where a maximum surface temperature criterion exists, the portion of the hot-channel factor related to the uncertainty in the film correlation can be satisfied by reducing the coefficient in the Dalle Donne correlation from 0.021 to 0.019. This reduction would account for those experimental points presently falling in the lower region of the ±10 percent error band.

Since no attempt was made to account for entrance effects related to the development of the boundary layer, empirical correction factors such as $1 + 0.3(L/D)^{-0.7}$ (ref. 9) may still be applicable.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 30, 1964.

APPENDIX - SYMBOLS

A Reynolds number exponent defined in eq. (1)

B Prandtl number exponent defined in eq. (1)

C temperature ratio exponent defined in eq. (1)

c_p specific heat of gas at constant pressure, Btu/(lb)(°R)

D hydraulic diameter, ft

G mass flow rate, lb/(sec)(sq ft)

h local heat-transfer coefficient, Btu/(sec)(sq ft)(°R)

k thermal conductivity, Btu/(sec)(ft)(°R)

K constant in heat-transfer equation defined in eq. (1)

L distance from entrance, ft

Nu Nusselt number, hD/k

Pr Prandtl number, $c_p\mu/k$

Q heat-transfer rate, Btu/sec

Re Reynolds number, GD/μ

S heat-transfer area, sq ft

T temperature, °R

x refers to defined reference temperature defined in eq. (12)

α viscosity proportionality constant defined in eqs. (10)

β thermal conductivity proportionality constant defined in eqs. (10)

γ specific heat proportionality constant defined in eqs. (10)

μ absolute viscosity, lb/(sec)(ft)

φ ratio of physical properties

Subscripts:

b conditions of bulk fluid

exp experimental

f conditions in film

w conditions at wall

x conditions at a defined reference point

0 condition at design point

1 condition at off-design point

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